

**Biological Evaluation of
Hemlock Woolly Adelgid at
New River Gorge National River and
Gauley River National Recreation Area,
West Virginia**

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Photo Credit: Tim Tomon

Prepared by

Danielle Martin, Pathologist
USDA Forest Service
State and Private Forestry
Forest Health Protection

And

Douglas Manning, Biologist
New River Gorge National River
Gauley River National Recreation Area

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ABSTRACT

In the summer of 2020, National Park Service, West Virginia Department of Agriculture and USDA Forest Service personnel conducted surveys to evaluate hemlock woolly adelgid (HWA), *Adelges tsugae* population densities and to assess the need for treatment at the New River Gorge National River (NERI), the Gauley River National Recreation Area (GARI) and the Bluestone National Scenic River (BNSR). Current populations are sufficient in most areas to impact tree health. Treatments using imidacloprid on accessible, individual, high-valued, infested hemlock trees and the release of natural enemies are recommended in the Burnwood, Fern Creek, upper Wolf Creek, Kaymoor, South Nuttall, Grandview, and Kates Branch areas of NERI, and Hedricks Creek area and Koontz Bend area of GARI.

INTRODUCTION

HEMLOCK WOOLLY ADELGID

Adelgids are small, soft-bodied insects that feed exclusively on conifers. The family is divided into two genera: *Adelges* and *Pineus*. There are six species of *Adelges* that occur in North America, of which only one is native (Montgomery 1999), the Cooley spruce gall aphid (*Adelges cooleyi*). This adelgid occurs coast to coast in northern North America. Its primary hosts are recorded as white (*Picea glauca*), blue (*Picea pungens*), Sitka (*Picea sitchensis*), and Engelmann (*Picea engelmannii*) spruce (Baker 1972). It has an alternate host, Douglas fir (*Pseudotsuga menziesii*). There are 10 species of *Pineus* that occur in North America, of which seven are native. Four of these the pine bark adelgid (*Pineus strobi*); the pine leaf adelgid (*P. pinifoliae*); the red spruce adelgid (*P. floccus*); and the spruce gall adelgid (*P. similes*) seem to be indigenous to eastern North America (Drooz 1989, Montgomery 1999). These species attack eastern white pine (*Pinus strobus*), red spruce (*Picea rubens*), and black spruce (*Picea mariana*) but seldom cause extensive damage (Drooz 1989, Montgomery 1999). Little is known about the population dynamics, ecological role, or the predator complex associated with these native adelgids.

Native to Japan, the hemlock woolly adelgid (*Adelges tsugae*) is a pest of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*T. caroliniana*) (Onken et al. 1999), both of which are considered highly susceptible to the adelgid, with no documented resistance (Bentz et al. 2002). The latter tree species is found only in the southern region of the Appalachian Mountains (Onken et al. 1999). HWA is currently established in 17 eastern states from Georgia to Maine, and tree decline and mortality have increased at an accelerated rate since the late 1980s. For example, in the Shenandoah National Park (SNP), hemlock crown health has declined since the early 1990s. In 1990, greater than 77 percent of the hemlocks sampled were in a “healthy” condition; by 1998, less than 10 percent were in a “healthy” condition (Akerson and Hunt 1998). In another study at SNP,

tree mortality significantly increased from an initial 8 percent in 1990 to nearly 50 percent in 2000 (Bair 2002). As of 2005, hemlock mortality at SNP was almost 95 % (Onken and Souto 2006). In New Jersey twelve years after initial HWA infestations, tree mortality reached more than 90% in some hemlock stands (Mayer et al 2002).

The hemlock woolly adelgid is parthenogenetic (an all-female population with asexual reproduction) that has six stages of development: the egg, four nymphal instars, and the adult, and two generations a year on hemlock. The winter generation, the sistens, develops from early summer to midspring of the following year (June-March). The spring generation, the progrediens, develops from spring to early summer (March-June). The generations overlap in mid to late spring.

The hemlock woolly adelgid is unusual in that it enters a period of dormancy during the hot summer months. Prior to dormancy, the nymphs produce a tiny halo of wool-like wax filaments surrounding their bodies. The adelgids begin to feed once cooler temperatures prevail, usually in October and continue throughout the winter months. As it matures this woolly covering increases in size and becomes more conspicuous. This woolly sac (ovisac) helps protect the insect and its eggs from natural enemies and prevents them from drying out. These ovisacs can be readily observed from late fall to early summer on the underside of the outermost branch tips of hemlock trees.



Figure 1. Hemlock woolly adelgid nymphs in dormancy.



Figure 2. Hemlock woolly adelgid ovisacs (woolly sac).

The ovisacs of the winter generation contain up to 300 eggs, while the spring generation ovisacs contain between 20 and 75 eggs. The hemlock woolly adelgid also has a winged form that is produced by the spring generation. This form must complete part of its life cycle on spruce. The apparent lack of a suitable spruce host for this form in eastern North America results in a substantial loss of adelgids each year (McClure 1992b). Although natural mortality in HWA populations is commonly between 30 to 60 percent (McClure 1989, 1996), the reproduction potential of this insect remains high. Other mortality is generally attributed to two likely causes: 1) an extended period of cold temperatures or rapid temperature changes that coincides with a susceptible period of development for the adelgid, and/or 2) a sufficient loss in the nutritional quality and

quantity of the food source, which is associated with the decline in health and vigor of the host tree (McClure 1996, Onken et al. 1999).

Adelgid feeding can kill a mature tree in about 5 to 7 years (McClure et al. 2001). This tiny insect (~ 1 mm) feeds on all size classes of hemlock, from seedling to mature, old growth tree. The first instar nymphs, called crawlers, search for suitable sites at the base of the hemlock needles, and insert their feeding stylets into the young hemlock twigs. Once settled the adelgid is committed to that feeding site throughout the remainder of its development. The mouth parts of the adelgid, the stylet bundle, is more than three times the length of the insect and penetrates deep within the plant tissues. HWA does not deplete nutrients directly by feeding on the sap, but rather by depleting the food reserves from the tree's storage cells (McClure et al. 2001). These food reserves are necessary for the production of new growth in the following year.

Dispersal and movement of HWA during its egg and mobile first instar stages is associated with wind, birds, deer, and other forest dwelling mammals. Humans also move the adelgid during logging and recreational activities and movement of infested nursery stock (McClure 1995). Natural enemies native to eastern North America are not capable of maintaining low-level HWA populations (Van Driesche et al. 1996, Wallace and Hain 1998).

HWA was first reported in the western U.S. in the 1920s (Annand 1924, McClure 2001). HWA populations on western tree species, including western hemlock (*Tsuga heterophylla*) and mountain hemlock (*T. mertensiana*), appear to be innocuous; these tree species are believed to be resistant because little damage has been reported (McClure 2001). Unfortunately, both these trees are of limited value for hybridization and planting due to their poor adaptation to the east coast environment (Bentz et al. 2002). In the East, HWA was first reported in 1951 near Richmond, Virginia. It was considered to be more of an urban landscape pest and was controlled using a variety of insecticides applied with ground spraying equipment. Observations of the adelgid were periodically reported in several Mid-Atlantic States in the 1960s and 1970s but it was not until the 1980s that HWA populations began to surge and spread northward to New England at an alarming rate. By the late 1980s to early 1990s, infestations of HWA were reported to be causing extensive hemlock decline and tree mortality in hemlock forests throughout the East (McClure 2001).

Recent phylogenetic analyses indicates that HWA in eastern North America likely originated from southern Japan while HWA found in western North America represents a separate lineage (Havill et al. 2006). The standing theory is that HWA found in western North America is native to that region and western hemlocks have co-evolved with this pest. This theory is further supported when we consider that at least one host specific natural enemy, *Laricobius nigrinus*, is also only found in western North America.

HEMLOCK IMPORTANCE

Eastern hemlock is an extremely shade tolerant tree species, capable of surviving for as long as 350 years underneath a shaded forest canopy (Quimby, 1996). It is a slow-growing long-lived tree. It may take 250-300 years to reach maturity and may live for 800 years or more (Godman and Lancaster 1990). Eastern hemlock forests create distinctive microclimates and provide important habitat for a variety of wildlife, such as birds, fish, invertebrates, amphibians, reptiles and mammals. In the Northeast, 96 bird and 47 mammal species are associated with hemlock forests at some point during their life (Yamasaki et al. 2000). Hemlocks create a cooling effect in summer that is a critical factor in supporting trout populations. Studies have shown that removal of hemlock trees within 80 feet of a stream can cause temperatures to rise 6 to 9 degrees Celsius (Lapin 1994).

NERI, GARI, BLUE are USDI Park Service sites located in Fayette, Raleigh, Summers, Mercer, and Nicholas counties in West Virginia and cover 72,189 acres, 11,507 acres, and 4,310 acres, respectively. Hemlock trees are a common component of the plant community at these three parks and form almost pure stands along many of the narrow high-gradient stream corridors and are co-dominant canopy trees on 10,190 acres. Old growth hemlock stands ranging between 100 and 200 years old are scattered throughout these parks and there are a couple that are approaching 300 years old at GARI (Perez 2005).

Hemlock forests provide significant contribution to the ecological, recreational, and aesthetic values of these parks. Many waterfalls and wetlands are associated with hemlock forests and recreational activities such as hiking, trout fishing, bird watching, general “sight-seeing”, and picnicking are very popular and concentrated in these areas. Rare bird species including Swainson’s warbler, blue-headed vireo, Cerulean warbler and Louisiana waterthrush are found only in areas where hemlock is a major component of the plant community.

MONITORING AND MANAGEMENT ACTIVITIES

In 1999, the NPS established a long-term hemlock forest monitoring program (Perez, 2005). Thirty-six 400m² sampling plots were selected in GARI and NERI hemlock stands. No plots were established at BLUE due to logistical constraints. The objective of the study was to gather information on hemlock health, HWA infestation levels, biodiversity and rare, threatened and endangered species.

HWA was first detected within the park boundaries along the Bluestone River in 2000 (Perez, 2000). By 2005, HWA was found in 8 of the 36 monitoring plots (22%) at NERI and GARI. Trees along the Bluestone River have been infested the longest, and currently exhibit declining tree health.

In 2007, the park established a Cooperative Agreement with West Virginia University to resample all of the vegetative parameters including a bird survey. This will be the first

comprehensive inventory since the plots were established in 1998. A final report is expected in spring 2008.

In 2003, the park initiated a HWA management program, and funding and technical assistance has since been provided by the USDA Forest Service. Program goals include:

- Educate the visiting public and neighbors about HWA and the threat to the hemlock forest through a variety of media including newspapers, television, internet, and park sponsored interpretive programs.
- Inventory and monitor long-term trends within the hemlock ecosystems and document the effects of HWA on biological diversity and hemlock decline.
- Implement a suite of integrated pest management alternatives to mitigate the effects of HWA on the ecosystem including the use of biological and chemical controls.
- Continue to encourage and support research efforts to increase the knowledge and understanding of the ecological significance of the native hemlock forests.

The objectives of the suppression program are:

- Protect public health and safety in areas of the park with high visitor use, such as, picnic areas, overlooks, campgrounds, roads, and trail heads, through the reduction of hazardous trees created by the dead and dying hemlock trees.
- Preserve hemlock stands with large numbers of sensitive species where treatments are economically feasible and accessible to the public. Select a few exemplary hemlock stands and try to protect them in perpetuity.
- Protect federally protected species, hemlocks along high quality streams, and old growth forests where feasible.

Biological Control: Since 2005, the park, with assistance from the USDA Forest Service in Morgantown, WV, has been releasing predatory beetles in hemlock forests that contain outstanding resource values and located in areas inaccessible or impractical for chemical treatments. The releases have included *Laricobius nigrinus*, *Sasajiscymnus tsugae*, and *Scymnus sinuanodulus* predatory beetles (Table 1). Monitoring of the beetle release effort has been conducted by the US Forest Service and *Laricobius nigrinus* has been confirmed to be established at the Hedrick's Creek release sites.

Chemical Control: The NRG NPS has been working with the USDA Forest Service in Morgantown, WV, to administer chemical treatments for the control of HWA in high value sites. Since 2006, over 21,000 trees have been treated within the park (Table 2).



Figure 3. John Perez, Biologist from NERI releasing *Scymnus sinuanodulus* beetles in May 2007



Figure 4. *Laricobius nigrinus* beetle recovered at Hedrick's Creek in Fall 2006

Table 1. Predatory beetle releases at New River Gorge National River and Gauley River National Recreation Area.

Species	Release Date	# Released	Release Location	Recovery Date	# Recovered
L. nigrinus	11/2/2005	300	Hedrick's Creek (GARI)	4/17/2007	1
L. nigrinus	10/28/2008	224	Hedrick's Creek (GARI)	5/9/2013	25
L. nigrinus	11/13/2008	500	Hedrick's Creek (GARI)	10/28/2013	2
L. nigrinus	10/30/2009	300	Hedrick's Creek (GARI)	10/28/2013	2
L. nigrinus	10/30/2009	556	Hedrick's Creek (GARI)	11/4/2014	0
L. nigrinus	12/12/2006	310	Hedricks Creek #2 (GARI)	4/17/2007	1
L. nigrinus	12/12/2006	146	Burnwood Area #2 (NERI)	3/16/2011	18
L. nigrinus	10/28/2008	360	Burnwood Area #2 (NERI)	4/5/2012	25
L. nigrinus			Burnwood Area #2 (NERI)	10/12/2013	4
L. nigrinus			Burnwood Area #2 (NERI)	10/26/2015	1
L. nigrinus			Burnwood Area #2 (NERI)	10/16/2017	7
L. nigrinus			Burnwood Area #2 (NERI)	10/24/2018	3
L. nigrinus			Burnwood Area #2 (NERI)	10/25/2018	5
L. nigrinus	10/12/2012	5000	Burnwood Ranger Station (NERI)	11/28/2012	1
L. nigrinus			Burnwood Ranger Station (NERI)	10/21/2013	2
L. nigrinus			Burnwood Ranger Station (NERI)	5/8/2014	0
L. nigrinus	11/7/2007	500	Kaymoor-South Nuttail Road (NERI)	10/21/2013	4
L. nigrinus			Kaymoor-South Nuttail Road (NERI)	10/18/2017	1
L. nigrinus	10/1/2008	500	Meadow River-N of Carnifax Tunnel #1 (GARI)	3/17/2011	1

L. nigrinus			Meadow River-N of Carnifax Tunnel #1 (GARI)	10/28/2013	0
L. nigrinus	10/1/2008	500	Meadow River-S of Carnifax Tunnel #1 (GARI)	11/2/2009	1
L. nigrinus			Meadow River-S of Carnifax Tunnel #1 (GARI)	10/28/2013	0
L. nigrinus	11/7/2007	500	Upper Wolf Creek #2 (NERI)	10/22/2008	3
L. nigrinus	10/16/2008	1000	Upper Wolf Creek #3 (NERI)	4/5/2012	0
L. nigrinus			Upper Wolf Creek #3 (NERI)	4/25/2013	14
L. nigrinus			Upper Wolf Creek #3 (NERI)	10/21/2013	0
L. nigrinus	10/28/2008	75	Meadow River-Dogwood Creek #1 (GARI)	10/28/2013	4
L. nigrinus	11/1/2013	466	Meadow River- Meadow River Farm #2 (GARI)	11/4/2014	0
L. nigrinus	11/1/2013	585	Meadow River- Meadow River Farm #1 (GARI)	11/4/2014	0
L. nigrinus	11/24/2009	500	Fern Creek (NERI)	N/A	N/A
L. nigrinus	1/28/2010	500	Fern Creek (NERI)	N/A	N/A
L. nigrinus	10/28/2012	469	Fern Creek (NERI)	N/A	N/A
L. nigrinus	11/12/2010	2000	Wolf Creek (NERI)	12/6/2011	1
L. nigrinus	11/17/2010	2000	Wolf Creek (NERI)	4/25/2013	2
L. nigrinus			Wolf Creek (NERI)	10/21/2013	1
L. nigrinus			Wolf Creek (NERI)	10/30/2017	0
L. nigrinus	10/12/2012	954	Fayetteville Huse Cemetery (NERI)	10/12/2013	12
L. nigrinus	10/26/2012	865	Fayetteville Huse Cemetery (NERI)	5/8/2014	0
L. nigrinus	11/1/2013	100	Fayetteville Huse Cemetery (NERI)	11/4/2014	0
L. nigrinus			Fayetteville Huse Cemetery (NERI)	10/30/2017	0
L. nigrinus			Fayetteville Huse Cemetery (NERI)	11/6/2018	2
L. nigrinus	10/26/2012	1044	Martin Luther King Drive (NERI)	10/21/2013	3
L. nigrinus			Martin Luther King Drive (NERI)	11/6/2018	3
L. nigrinus	10/26/2012	968	Kates Branch #2 (NERI)	10/18/2013	5
L. nigrinus	11/1/2013	100	Kates Branch #2 (NERI)	11/25/2015	0
L. nigrinus			Kates Branch #2 (NERI)	10/20/2017	1
L. nigrinus	10/26/2012	960	Kates Branch #1 (NERI)	10/18/2013	2

L. nigrinus	11/1/2013	100	Kates Branch #1 (NERI)	11/25/2015	0
L. nigrinus			Kates Branch #1 (NERI)	10/20/2017	0
L. nigrinus	2/12/2013	1773	Arrowwood Creek/Meadow River (GARI)	10/31/2013	1
L. nigrinus			Arrowwood Creek/Meadow River (GARI)	10/31/2013	1
L. nigrinus	11/1/2013	100	Arrowwood Creek/Meadow River (GARI)	11/4/2014	0
L. nigrinus	10/27/2012	300	The Oaks Subdivision- Grandview Exit I-64 (GARI)	10/18/2013	3
L. nigrinus	11/1/2013	100	The Oaks Subdivision- Grandview Exit I-64 (GARI)	10/20/2017	0
L. nigrinus	11/15/2013	500	108 Huse Street Fayetteville (GARI)	11/4/2014	0
L. nigrinus	11/19/2014	500	109 Huse Street Fayetteville (GARI)	10/30/2017	0
L. nigrinus			110 Huse Street Fayetteville (GARI)	11/6/2018	1
L. nigrinus	11/15/2013	500	Confluence Resort (GARI)	N/A	N/A
L. nigrinus	10/20/2016	500	Beauty Mountain (NERI)	10/16/2017	1
L. nigrinus	10/24/2017	298	Beauty Mountain (NERI)	N/A	N/A
L. nigrinus	10/25/2017	500	Beauty Mountain (NERI)	N/A	N/A
S. tsugae	5/24/2006	5118	Lower Wolf Creek (NERI)	N/A	N/A
S. tsugae	5/31/2006	5000	Burnwood Area #1 (NERI)	N/A	N/A
S. sinuanodulus	5/1/2007	500	Upper Wolf Creek #1 (NERI)	N/A	N/A

Table 2. Acres Treated with HWA Chemical Control at New River Gorge National River and Gauley River National Recreation Area.

Chemical Control:

Year	# Trees	Acres
2006	1455	N/A
2007	2050	N/A
2008	1302	≥68.71
2009	3332	≥128.9
2010	1959	≥433.25
2011	374	≥98.5
2012	2007	128.05
2013	1090	72.75
2014	2268	120
2015	1973	123
2016	2018	99
2017	628	43.45
2018	500	49.25
2019	660	7.17



Figure 5. Chemical treatment using the Arborjet “Tree IV” system using Imajet insecticide.

SURVEY AREAS

Survey areas at the parks were chosen by NPS resource management staff based on ecological significance and/or visual importance. Hemlock at NERI is an important component of the forest canopy on about 5,990 acres (about 7%) of the total park acreage. The seven areas at NERI surveyed included Burnwood Area, Fern Creek, upper Wolf Creek, Kaymoor Mine Trail, South Nuttall, Grandview, Kates Branch, and Glade Creek.

Hedrick’s Creek (35 acres, GARI) Hemlock stands at GARI are an important component of the forest canopy on over 5,000 acres. GARI hemlock stands are sited in that park’s General Management plan as “Outstanding Natural Features” with “high intrinsic or unique values”. Hedrick’s Creek has old growth hemlock tress averaging 199 years old and some trees approaching 340 years old. Three-hundred *Laricobius nigrinus* were released in Hedrick’s Creek in November of 2005. *L. nigrinus* beetles were also released in December of 2006 (310 beetles). *L. nigrinus* were released along the Meadow River on September 1, 2008 (1000) and September 28, 2008 (75). *L. nigrinus* (886 beetles) were released at Hedrick’s Creek in October of 2009. Chemical treatments have not been applied at the Gauley River because the rugged terrain makes accessibility

extremely difficult. Long-term hemlock ecosystem monitoring plots have been established in Hedrick's Creek.

Burnwood (39 acres, NERI) is a publicly accessible mature mixed hardwood/hemlock forest. The 100 acre day use area is located across from the Canyon Rim Visitor Center. This area is used for educational school trips and is the location of the Lang Loop Forest Trail. Long-term hemlock ecosystem monitoring plots have been established here. Predatory beetles were released in May (5,000 *Sasajiscymnus tsugae*) and December (146 *L. nigrinus*) of 2006). In a separate part of the treatment area 252 trees were treated with a soil injection of imidacloprid.

Bridge Buttress and Junkyard Trail (15 acres, NERI) are two of NERI's most popular and highly used climbing areas, with beginner through advanced climbs and hiking trails. Hemlocks are an important part of this mixed forest and provide shade and cover for recreation. Trees in both of these areas were treated by soil injection in 2009.

Fern Creek (97 acres, NERI) is one of the more dense stands at NERI. Fern Creek is less than a mile from the New River Gorge Bridge and Canyon Rim Visitor Center. The Endless Wall Trail, located in the Fern Creek Area, is 2.4 miles long providing great views of the New River Gorge, and access to some of the best known climbing locations in the park. A large portion of the stand is within a riparian zone. Breeding populations of the Swainson's warbler have been documented at Fern Creek, and the rare green salamander is known to occur there as well. Both long-term ecosystem monitoring plots and treatment monitoring trees have been established in Fern Creek. A chemical treatment program was initiated in Fern Creek in 2006. Trees in Fern Creek have been treated with soil injections of imidacloprid, stem injections using the Arborjet "Tree IV" system along the creek, and CoreTect, with imidacloprid in tablet form. Predatory beetles were released in Fern Creek in November of 2009 (500 *L. nigrinus*).

Wolf Creek (267 acres, NERI) has hemlocks as a dominant component of the forest with overstory trees ranging from 80-200 years old. Breeding populations of the rare Cerulean and Swainson's warbler, along with rare amphibians and the Allegheny woodrat occur in this area. *S. tsugae* were released in lower Wolf Creek in May of 2006 (5,118 beetles). *Scymnus sinuanodulus* were released there in May of 2007. *L. Nigrinus* were released in upper Wolf Creek in November of 2007 and September of 2008. Chemical controls have not been used at Wolf Creek to date.

Kaymoor (16 acres, NERI) has a hiking trail that descends steeply to the abandoned Kaymoor Mine and provides a great overlook of the river and gorge as well as popular climbing areas. The forest here is an example of the rare rimrock community. Trees along the rim and trail were treated in 2007. The South Nuttal area is upriver of the Kaymoor area. 500 *L. nigrinus* were released in South Nuttal in November of 2007.

Grandview (154 acres, NERI) is one of the most popular outdoor vistas in West Virginia, with four developed overlooks with outstanding vistas and high visitor use. It is also home to Theatre West Virginia's Cliffside Amphitheatre. There are five trails from

3/8 to 2 ½ miles in length. Hemlocks frame the vistas and are a major component of the rare rimrock forest community in this area. The rare Allegheny woodrat has been documented within the hemlock forests and peregrine falcons have been successfully raised, or “hacked” along the cliff line. Grandview has been treated since 2006. Some trees treated in 2006 were retreated here in 2009 due to their declining appearance. Hemlock ecosystem monitoring plots and treatment and control trees are established at Grandview.

Glade Creek (134 acres, NERI) is one of the most popular trout streams in West Virginia. There is a 5.6 mile trail along the creek that contains pockets of hemlock. The creek has good to excellent water quality and a diverse ecosystem. Hemlocks at Glade Creek have been treated since 2006 by soil injection. Trees along Glade Creek appear to be declining more rapidly than other areas in the park. In 2009 some trees that were treated by soil injection in 2006 were retreated, as well as new soil injections and CoreTect treatments.

Kate’s Branch (42 acres, NERI) borders the 20 acre wetland complex, the largest in NERI and the site of several rare plants. Hemlocks contribute to the ecological integrity of this wetland and there is a trail that follows an old logging road through this area, and connects to the Glade Creek Trail. Trees in Kate’s Branch were treated in 2007 and 2009 with soil injection and CoreTect tablets.

Bluestone River (200 acres, BLUE) is a National Wild and Scenic River bordered by Pipestem and Bluestone State Park. There are hemlock forests on about 200 acres, 5% of the total park acreage. Populations of the federally threatened Virginia spiraea are found in the understory along the banks of the Bluestone River. The Bluestone River has good to excellent water quality and diverse aquatic ecosystems. Hemlock trees found along the floodplain and side tributaries contribute to the scenery and ecological function of this wild and scenic river. This is the first area where HWA was found in the park, in 2000, and many trees continue to have a stressed appearance. Hemlocks have been treated along the west side of the Bluestone River on a 3 mile section of trail downriver of Mountain Creek Lodge. Trees have been treated since 2006 by soil and stem injection. Treatment monitoring and control trees are located at BLUE.

METHODS

The survey method used for this evaluation of HWA populations was based on the sampling plan developed by Costa and Onken (2006). This sampling plan measures the infestation level of the stand rather than individual trees. A strong relationship has been established between the percentage of trees infested and the number of adelgids found on branches (Costa 2005). The sampling plan gives users a quick and precise way to both detect and characterize the severity of an infestation by determining the percentage of infested trees. The maximum number of trees to sample is set at 100, but as higher

numbers of infested trees are encountered, substantially less sampling is required. When nearly all of the trees contain adelgids, only eight trees need to be surveyed.

In addition to the stand level assessment, qualitative information regarding HWA densities on individual trees was also collected. On each branch, HWA densities were visually classified on each branch sample as heavy, moderate, light or none based on an estimated percentage of tips with adelgid present as follows:

Heavy (H) = >50% infested
Moderate (M) = 25% to 50% infested
Light (L) = <25% infested
None (N) = 0% infested

General tree stand health was classified by determining a vigor rating based on the following criteria:

Healthy (H) = tree appears to be in reasonably good health: less than 10% branch or twig mortality, discoloration, or dwarfed leaves present

Light Decline (LD) = branch mortality, twig dieback, foliage discoloration, or dwarfed leaves present on 10-25% of the crown

Moderate Decline (MD) = branch mortality, twig dieback, foliage discoloration or dwarfed leaves on 26-50% of crown

Severe Decline (SD) = more than 50% of the crown with branch mortality, dieback, discoloration or leaf dwarfing, but foliage still present indicating that the tree is alive

A GPS (global positioning system) unit was used to collect coordinates (decimal degrees, WGS84) and map the area surveyed within each park. A GPS point represented the general area of each stand.

RESULTS

A total of nine areas were surveyed within NERI, GARI, and BLUE: Burnwood area, Fern Creek, upper Wolf Creek, Kaymoor area, South Nuttall, Grandview, Kate's Branch, Glade Creek, Hedricks Creek, and Bluestone River. Inclement weather prevented the crew from surveying Glade Creek. This area will be surveyed later in the spring to determine the HWA populations and the need for treatment in this area. The survey areas are represented in Figures 7a-b, and a summary of the results is presented in Table 2.

All survey areas reached a STOP threshold of eight trees within the first block of the stand, indicating nearly all hemlock trees are infested with some level of HWA densities.

Stand level infestations ranged from 47 -100 percent. HWA densities within tree were observed to range from none to moderate among the survey areas.

In general hemlock conditions range from healthy to light decline within most of the survey areas, with exception of Bluestone River, where decline symptoms are more prevalent and range from light to severe decline.

Table 2. Summary of HWA survey data collected in 2020 at NERI, GARI, and BLUE.

Location	Number of Trees Surveyed	Stand Level Infestation (%) ¹	Tree Level Infestation Range ²
Burnwood Area (NERI)	8	100	L-H
Fern Creek (NERI)	8	100	L-M
Wolf Creek (NERI)	8	100	L-M
Kaymoor (NERI)	8	100	L-M
Grandview (NERI)	8	100	L-M
Kate's Branch (NERI)	8	100	L-H
Hedricks Creek (GARI)	8	100	L-M
Bluestone (BLUE)	8	100	L-M
South Nuttall (NERI)	8	100	L-M

¹HWA stand level infestation percentage = STOP threshold (8 trees)/ number of trees surveyed

²HWA infestation densities on individual trees were designated by visually inspecting each branch sample based on an estimated percentage of tips with adelgid present and categorized as follows:

Heavy (H) = >50% infested
Moderate (M) = 25-50% infested
Light (L) = <25% infested
None (N) = 0% infested

Figure 7a. Hemlock woolly adelgid survey locations at New River Gorge National River, the Gauley River National Recreation Area, and the Bluestone National Scenic River, winter/spring, 2008.

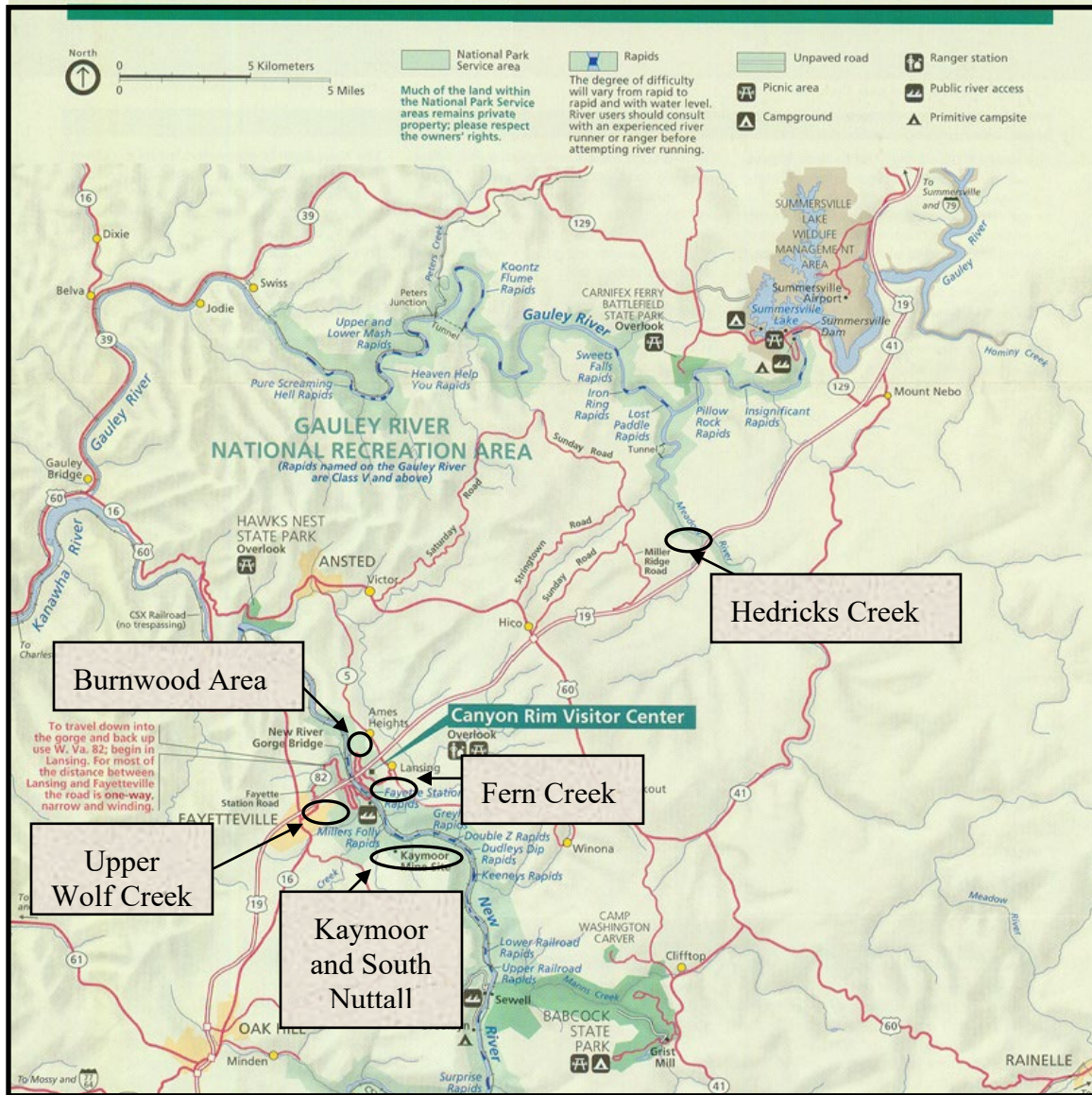
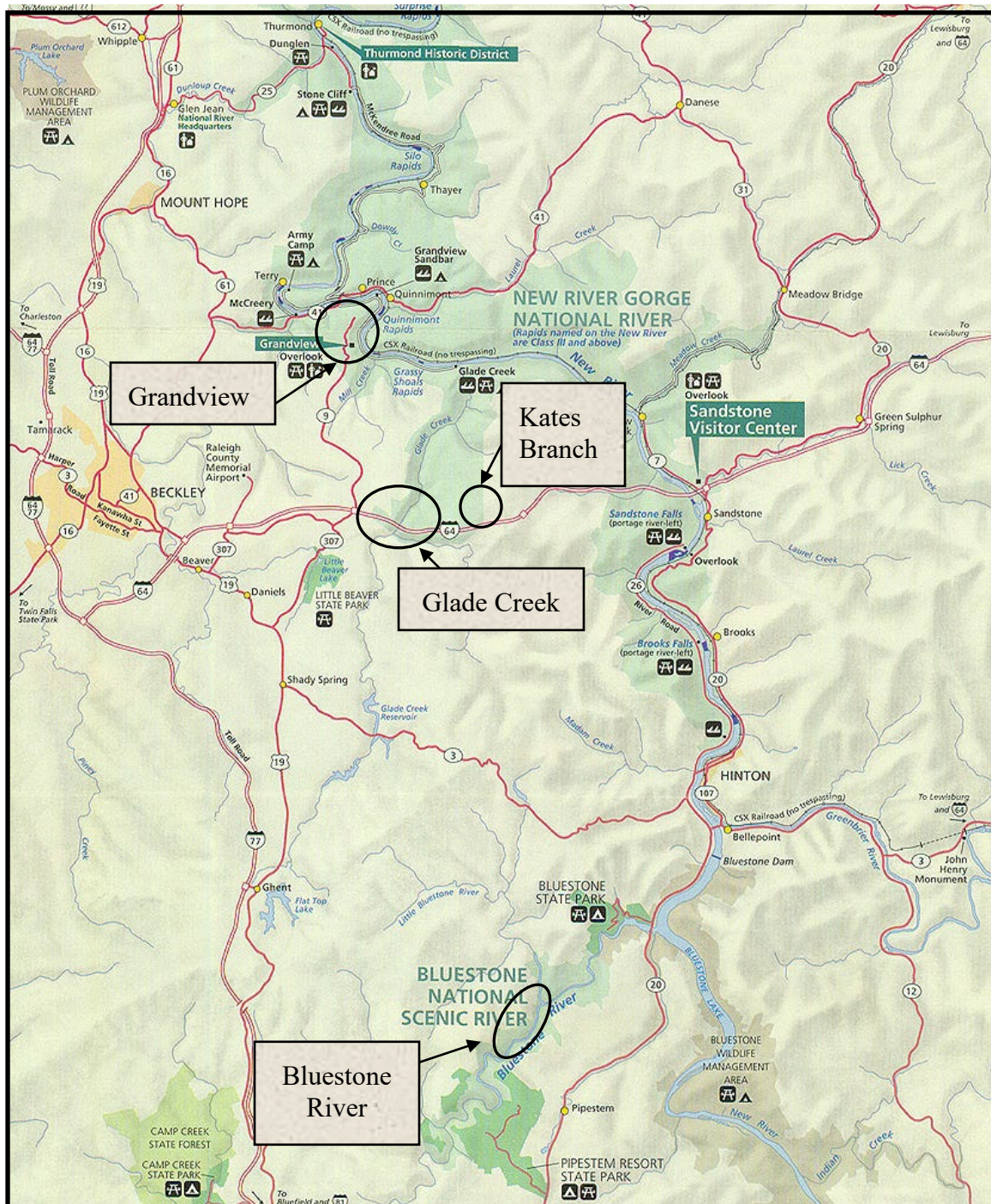


Figure 7b. Hemlock woolly adelgid survey locations at New River Gorge National River, the Gauley River National Recreation Area, and the Bluestone National Scenic River, 2020.



DISCUSSION

HWA populations are generally low to moderate throughout most of the survey areas. HWA densities are highly variable between trees, ranging from none to moderate, but all sites have an established population. Predicting year to year changes in HWA densities is difficult because of the dynamic nature of the many variables involved. Factors such as future climatic conditions, changing micro habitat (tree and site) conditions and other biotic and abiotic factors affect both survival and fecundity of HWA. However, the pattern of abundance and distribution is conducive to outbreak populations when conditions are favorable. Consequently, impacts to hemlock resources throughout NERI, GARE, and BLUE will continue to increase.

MANAGEMENT CONSIDERATIONS

Chemical management options for protecting hemlock stands are limited by the biology and feeding behavior of HWA, pest population densities, site conditions (i.e. proximity to streams), accessibility and limited application technology currently available. Insecticide treatments although effective, are conducted on an individual tree basis which can be both labor intensive and costly. Thus, treatment strategies are typically focused in high value sites such as recreational or scenic areas or where hemlock stands have an important ecological role or genetic preservation is a high priority. Classical biological controls such as predators and pathogens are being pursued by the USDA Forest Service but will likely take years to become effectively established. As such, preservation of hemlocks in the short term will require intensive monitoring and periodic chemical treatments when infestations are discovered.

Foliar Chemical Treatments: Aerial spray using horticultural oil or insecticidal soap is not an option because aerial sprays could not provide the needed "saturation" necessary to ensure that the insecticide adequately covers the insect. Aerial spraying with more toxic insecticides (e.g. malathion or diazinon) would have very significant, unacceptable impacts on a wide range of non-target insects and other animals and limited control benefits (Evans 2000). Application of insecticides using ground spraying equipment is generally limited to areas accessible to hydraulic spray equipment and areas where over spray or run off would not contaminate streams, lakes or ponds. Backpack sprayers could be effectively used for foliar treatment of infested seedlings and saplings to protect regeneration.

Systemic Insecticides: Several systemic insecticides are labeled for adelgids and can be injected or implanted into hemlock trees. Imidacloprid is by far the most common systemic insecticide being used to control HWA and is either injected into the tree or applied in tablet form into the soil around hemlock trees. These insecticides are absorbed and trans-located by the vascular system of the tree to feeding adelgids and will effectively suppress HWA populations (Doccola et al. 2003, Webb et al. 2003, Evans 2000, Steward and Horner 1994, McClure 1992a). Soil injection in sandy or saturated soils should be avoided as leaching of imidacloprid into the soil profile and groundwater (McAvoy et al. 2002) is a possibility. Soil injections immediately adjacent to creeks or

other open waters and areas prone to frequent flooding should be avoided. Imidacloprid formulated as a trunk injection is available under the trade names Pointer®, IMA-jet® and Imicide® and are labeled for tree injection for the control of adelgids. Both stem and soil treatments of imidacloprid have become the preferred treatment for HWA in high value hemlock stands by state and federal resource managers.

Imidacloprid is an insecticide in the family of chemicals called neonicotinoids (Felsot 2001) in the chloronicotinyl subgroup (USDA Animal and Plant Health Inspection Service 2002). It has a mode of action similar to that of the botanical product nicotine, functioning as a fast-acting insect neurotoxicant (Schroeder and Flattum 1984) that binds to the nicotinic receptor sites in the postsynaptic membrane of the insect nerve (USDA Animal and Plant Health Inspection Service 2002), mimicking the action of acetylcholine, and thereby heightening, then blocking, the firing of the postsynaptic receptors with increasing doses (Schroeder and Flattum 1984, Felsot 2001). Because imidacloprid is slowly degraded in the insect, it causes substantial disorder within the nervous system, leading in most cases to death (Mullins 1993, Smith and Krischik 1999).

Imidacloprid is considered to have low to moderate mammalian toxicity (Mullins 1993), largely because it does not bind nerve receptors in mammals sufficiently to trigger nervous activity (Felsot 2001). The selective toxicity of imidacloprid is perhaps best illustrated by its use in flea treatments approved for cats and dogs. Advantage® is applied directly to the animal's skin; this preparation carries very little, if any, risk to the animal or to the people, including children, who may handle the animal (USDA Animal and Plant Health Inspection Service 2002). Chronic (repeated dose) toxicity studies have demonstrated that imidacloprid is not carcinogenic and is not mutagenic and demonstrates no primary reproductive toxicity (Mullins 1993). In studies of metabolic fate in rats, imidacloprid was rapidly absorbed and eliminated in the excreta (90 percent of the dose within 24 hours) with little bioaccumulation (0.5 percent of the dose after 48 hours) and no biologically significant differences occurring between sexes, dose level, and route of administration (USDA Animal and Plant Health Inspection Service 2002). Imidacloprid is an insecticide exhibiting both systemic and contact activity. The spectrum of activity primarily includes sucking insects (aphids, whiteflies, leaf and plant hoppers, thrips, plant bugs, and scales), many Coleopteran species, and selected species of Diptera and Lepidoptera. Activity has also been demonstrated for ants (Hymenoptera); termites (Isoptera); and cockroaches, grasshoppers, and crickets (Orthoptera). No activity has been demonstrated against nematodes or spider mites (Mullins 1993). In spider mites, imidacloprid has been demonstrated to cause an egg-laying enhancement (James and Price 2002). Since spider mites can be a problem in ornamental hemlocks, open-grown imidacloprid-treated trees should be carefully monitored for increases in mite populations.

Laboratory studies have shown that imidacloprid bioaccumulates in anurans and spotted salamanders and causes sublethal effects. Recent research conducted in WV shows strong evidence that salamanders and stream invertebrates bioaccumulate imidacloprid which leaches from HWA treatments (Crayton, 2019). Imidacloprid is associated with sublethal effects in salamanders, including reduced body condition and increased corticosterone

levels (Crayton, 2019). Imidacloprid exposure causes physiological changes, bioaccumulation, and reduced survival in anurans, and induces physiological impairment and reduced survival in benthic macroinvertebrates (Crayton, 2019).

Trunk-injected imidacloprid generally requires a week or longer to provide adelgid control, with protection lasting for up to 2 years. The soil injection or soil drench methods of imidacloprid treatments can take several months for translocation to occur but typically has provided better consistency in treatment efficacy and is expected to provide control for approximately 5 years. Stem injections should not be used on severely stressed trees.

Biological Control: There are no known parasites of adelgids. There are three predatory beetles approved for release and each is unique in its dispersal, reproductive potential, feeding behavior, and suitable climate regimes. They are all very host specific. Where these natural enemies are released is the responsibility of state forest health specialists from each state and the USFS. All of the releases are in infested hemlock stands found primarily along the leading edge of the generally infested area, where hemlocks are still healthy and HWA densities have not yet overwhelmed the trees. The release and establishment of HWA natural enemies is not likely to provide short term control of HWA. It is considered to be a long-term approach and will likely require a complex of natural enemies to maintain HWA below damaging levels. It may be years before these predators can self perpetuate sufficiently before any level of success can be determined.

The first predator beetle to be imported and released for biological control is a tiny, black lady beetle, *Sasajiscymnus tsugae*, from Japan. Since 1995, millions of *S. tsugae* beetles have been released in over 200 sites in 16 eastern states from Georgia to Maine. The recovery of *S. tsugae* beetles in the years following release have been sporadic. The number of beetles recovered have rarely been more than one or two per site. Adult beetles have been captured near some of the release sites more than 6 years after release, and some more than 1/2 a mile from nearest release site.

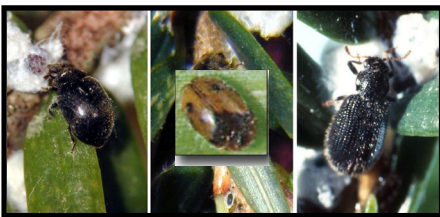


Figure 8. Beetles released for biocontrol (left to right): *Sasajiscymnus tsugae* from Japan, *Scymnus sinuanodulus* from China and *Laricobius nigrinus* from Pacific Northwest.

Another predatory beetle, *Scymnus sinuanodulus*, a lady beetle from China, has been released since 2005. More than 36,000 adult beetles have been released in eight states. So far, few beetles have been recovered from the release sites.

Two *Laricobius* beetles from the family Derodontidae also feed on adelgid. Two species are currently being reared, collected and released as HWA biocontrols are *Laricobius nigrinus*, from the Pacific Northwest and *L. osakensis* from Japan. Mass rearing of *L. nigrinus* began in 2003. Since then, more than 400,000 beetles have been released in hundreds of sites. Recovery of *L. nigrinus* has been confirmed at most sites. At some release sites, adult beetles are easily found, and hundreds of *L. nigrinus* larvae have been recovered. *L. osakensis* was first released in 2012 and has since

been released in more than 60 locations. As this is a newly released species, establishment success is still being examined.

An additional biological control agent under consideration are *Leucopis* silver flies. These are adelgid-specialist predators active during the late spring season. These predatory flies have been collected and shipped to the eastern U.S for caged release studies since 2015. With continued releases the western silver flies may be able to become established and become an important biocontrol agent.

Release of predator beetles should not take place in close proximity of hemlock trees that have received imidacloprid treatments. Preferred release sites are newly infested sites where trees and adelgids are still healthy. Older infested sites where adelgid densities are low and recovery of hemlock trees is evident has also proven acceptable. Predator beetles are laboratory reared and the number of predators available in any given year is variable depending in part, on the success of the rearing facilities to locate good quality host material for a food source. Artificial diets are not yet available.

RECOMMENDATIONS

Systemic insecticide treatments using imidacloprid are recommended for HWA control on accessible, individual, high-valued, infested hemlock trees in all the surveyed areas. The continued release and establishment of *Sasajiscymnus tsugae*, *Scymnus sinuanodulus*, and *Laricobius nigrinus* predatory beetles is also recommended in infested areas that are not in close proximity to chemical treatments. The highest value trees located in recreational areas are given priority for chemical treatment. Managers should consider a diversity of canopy positions when choosing trees to receive chemical treatment. Large hemlock trees may be good candidates for perpetual chemical protection given their high ecological or aesthetic value. However, depending on stand composition, it may be beneficial to chemically treat some mid-story or understory trees. This could serve to promote stand structural diversity and the presence of canopy-dominant hemlocks in the future. Caution should be applied when treating hemlocks in riparian areas, and soil applications should not be made within 3 m (10 ft) of a stream channel, lake, pond, or wetland.

Where possible, soil treatments are preferred over stem injections as they are less costly, offer more consistency in treatment efficacy and longer protection. Imidacloprid, and all pesticides, should be applied at the recommended label rate. The amount of imidacloprid applied should not exceed 0.45 kg of active ingredient per ha (0.4 lbs per ac) per year. Dinotefuran application should not exceed 0.6 kg of active ingredient per ha (0.54 lbs per ac) per year. Hemlocks tend to have faster uptake of the stem injected insecticides in the mornings during the spring and fall months when cooler temperatures and higher humidity prevail.

Imidacloprid treated trees should be marked in a manner that will identify the year they were treated, such as a basal spray of color coded paint or tags. Trees that receive the full rate of the insecticide and are retreated on an interval that maintains protection from

HWA for as long as possible. If using imidacloprid, trees are retreated approximately every 5–7 years or when chemical protection wears off (based on observance of HWA on the branches). No predators are released on these trees.

With treatment options comes the potential for non-target effects; land managers must balance the risk of these effects with the potential benefits that come with the control of the HWA. As a best management practice, the USFS has previously recommended that hemlocks within 50 feet of open water be treated with a stem injection rather than a soil treatment. Research at the CT Agricultural Experiment Station has recently demonstrated that imidacloprid binds tightly with organic soils such that movement more than a few centimeters is unlikely when the chemical is placed in the organic layer of the soil. Imidacloprid will leech through mineral soils quite readily and it is critical applicators use good judgment as to placement of the injector tip in organic soils which in most cases, is less than 3 inches deep. This depth also coincides with the shallow feeder roots of eastern hemlock. With this new research information, soil treatments closer to open water may be acceptable when treatment decisions are based on the soil conditions surrounding each tree to be treated within the 50-foot buffer. In circumstances where rocky porous soils exist or the organic layer is not sufficiently deep enough to handle the injector tip placement, trees should be treated using a stem injection system. Ground spraying using horticultural oil to protect hemlock seedlings and saplings by means of a backpack sprayer should be considered in areas where protecting younger hemlocks is desirable and where over spray or run off would not contaminate streams, lakes or ponds. One or two applications of a 2% solution of horticultural oil applied in early summer or early fall is recommended as adelgids have not yet developed the wool covering that can impede penetration of the insecticide.

Resource managers should continue to annually monitor tree health conditions, adelgid population densities and treatment efficacy. It is not logistically or economically feasible to chemically treat all trees in numerous or large hemlock stands. Therefore, resource managers must prioritize treatment areas and select individual, accessible, high valued, infested hemlock trees for treatment.

Predatory beetle releases take place in the spring or fall of the year when HWA are actively feeding. The establishment of these natural enemies offers potential long-term control and may minimize the need for repeated chemical treatments in future years. The release of HWA natural enemies within the park should continue.

Recent research suggests that elevated levels of sunlight, and associated elevated temperatures, have negative effects on adelgids and beneficial effects on infested hemlock trees. Silvicultural treatments, such as thinning and gap creation may enhance hemlock resilience in the presence of HWA. While management recommendations based on this research are still in development, specific silvicultural design recommendations could be integrated strategically with chemical treatments in order to improve the health and longevity of hemlocks in the stand. In the meantime, it is worth noting that hemlocks located in small canopy gaps, along forest edges, or in other environments with elevated

light levels may be good candidate trees for predator releases, provided they are infested with HWA at the time of release.

REFERENCES

- Akerson, J. and G. Hunt. 1998. HWA status at the Shenandoah National Park. USDA, Forest Service. Hemlock Woolly Adelgid Newsletter # 3: 10-11.
- Annand, P.N. 1924. A new species of *Adelges* (Hemiptera: Phylloxeridae). Pan-Pac. Entomol. 1: 79-82.
- Avery, M.L., D.G. Decker, D.L. Fisher and T. R. Stafford. 1993. Response of captive blackbirds to the new insecticidal seed treatment. J. Wildl. Manage. 57(3): 652-656.
- Bair, M.W. 2002. Eastern Hemlock (*Tsuga Canadensis*) Mortality in Shenandoah National Park. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 62-66p.
- Baker, W.L. 1972. Eastern forest insects. USDA, Forest Service. Miscellaneous Publication No. 1175. 642 p.
- Bentz, S.E., L.G.H. Riedel, M.R. Pooler, and A. Townsend. 2002. Hybridization and self-compatibility in controlled pollinations of eastern north American and asian hemlock (*Tsuga*) species. Journal of Arboriculture 28(4): 200-205.
- Butin, E., M. Montgomery, N. Havill, and J. Elkinton. 2002. Pre-release host range assessment for classical biological controls: Experience with predators for the hemlock woolly adelgid. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 205-213 p.
- Brantley, S.T.; Mayfield, A.E.; III; Jetton, R.M.; Miniati, C.F.; Zietlow, D.R.; Brown, C.L.; Rhea, J.R. 2017. Elevated light levels reduce hemlock woolly adelgid infestation and improve carbon balance of infested eastern hemlock seedlings. Forest Ecology and Management 385: 150–160.
- Chaney, W.R. 1986. Anatomy and physiology related to chemical movement in trees. Journal of Arboriculture 12(4): 85-91.
- Cheah, C.C. 1998. Establishing *Pseudoscymnus tsugae* (Coleoptera: Coccinellidae) as a biological control agent for hemlock woolly adelgid. Environmental Assessment prepared by the Connecticut Agricultural Experiment Station. Unpub. Report. 6 p.
- Cheah, C. A. S.-J. and M.S. McClure. 2000. Seasonal synchrony of life cycles between the exotic predator, *Pseudoscymnus tsugae* (Coleoptera: Coccinellidae) and its prey,

- the hemlock woolly adelgid *Adelges tsugae* (Homoptera: Adelgidae). *Agric. and For. Entom.* 2:241-251.
- Costa, S.D. 2005. Sampling for detection and monitoring of hemlock woolly adelgid within hemlock stands. Proceedings, Third symposium on hemlock woolly adelgid in the Eastern United States; Ashville, NC. FHTET-2005-01. Morgantown, WV: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team; 57-62.
- Costa, S. and B. Onken. 2006. Standardized Sampling for Detection and Monitoring of Hemlock Woolly Adelgid in Eastern Hemlock Forests. FHTET-2006-16. U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team; 11p.
- Crayton, Sara M., "Stream Salamander and Benthic Macroinvertebrate community Responses to imidacloprid exposure" (2019). *Graduate Theses, Dissertations, and Problem Reports*. 4015. <https://researchrepository.wvu.edu/etd/4015>
- Doccola, J.J. P.M. Wild, I. Ramasamy, P. Castillo, and C. Taylor. 2003. Efficacy of arborjet viper microinjections in the management of hemlock woolly adelgid. *Journal of Arboriculture*. 29(6): 327-330.
- Drooz, A.T. 1989. Insects of eastern forests. USDA, Forest Service. Micellaneous Publication No. 1426. 608 p.
- Evans, R.A. 2000. Draft Environmental Assessment: for the Release and Establishment of *Pseudoscymnus tsugae* (Coleoptera: Coccinellidae) as a Biological Control Agent for Hemlock Woolly Adelgid (*Adelges tsugae*) at the Delaware Water Gap National Recreation Area. USDI, National Park Service, Northeastern Region. 23 p.
- Felsot, A. 2001. Admiring Risk Reduction: Does Imidacloprid have what it takes? *Agrichemical and Environmental News* 186: 2-13.
- Godman, R.M. and K. Lancaster. 1990. *Tsuga canadensis* (l.) Carr., eastern hemlock. In: R.M. Burns and B.H. Honkala, eds. *Silvics of North America*, vol.1, conifers. USDA Forest Service, Agriculture Handbook No. 654. pp. 604-612.
- Havill, N.P., M.E. Montgomery, G.Yu, S. Shiyake, and A. Caccone, 2006. Mitochondrial DNA from Hemlock Woolly Adelgid (Hemiptera: Adelgidae) Suggests Cryptic Speciation and Pinpoints the Source of the Introduction to Eastern North America., Vol. 99 *Ann. Entomol. Soc. Amer.*, p. 195-203.
- Helms, J.A., ed. 1998. *The dictionary of forestry*. The Society of American Foresters. Bethesda, MD.

- Hennessey, R.D. and M.S. McClure. 1995. Field release of a non-indigenous lady beetle, *Pseudoscymnus* sp. (Coleoptera: Coccinellidae), for biological control of hemlock woolly adelgid, *Adelges tsugae* (Homoptera: Adelgidae). Environmental Assessment prepared by USDA, Animal and Plant Health Inspection Service, Riverdale, MD. Unpub. Report. 6 p.
- Hepting, G.H. 1971. Diseases of forest and shade trees of the United States. USDA Forest Service, Agricultural Handbook 386. 488-491.
- Hickin, M.; Preisser, E.L. 2015. Effects of light and water availability on the performance of hemlock woolly adelgid (Hemiptera: Adelgidae). *Environmental Entomology* 44: 128–135.
- James, D.G. and T.S. Price. 2002. Imidacloprid boosts TSSM egg production. *Agrichemical and Environmental News* 189: 1-11.
- Jenkins, J.C., J.D. Aber, and C.D. Canham. 1999. Hemlock woolly adelgid impacts on community structure and N cycling rates in eastern hemlock forests. *Canadian Journal of Forest Research* 29: 630-645.
- Kohler, G.R.; Stiefel, V.L.; Wallin, K.F.; Ross, D.W. 2008. Predators associated with the hemlock woolly adelgid (Hemiptera: Adelgidae) in the Pacific Northwest. *Environmental Entomology* 37: 494–504.
- Kohler G.R.; Wallin, K.F.; Ross, D.W. 2016. Seasonal phenology and abundance of *Leucopis argenticollis*, *Leucopis piniperda* (Diptera: Chamaemyiidae), *Laricobius nigrinus* (Coleoptera: Derodontidae) and *Adelges tsugae* (Hemiptera: Adelgidae) in the Pacific Northwest USA. *Bulletin of Entomological Research* 106: 546–550.
- Lapin, B. 1994. The Impact of Hemlock Woolly Adelgid on Resource in the Lower Connecticut Valley. USDA. Northeastern Center for Forest Health research, Hamden, CT. 45p.
- Mayer, M., R. Chianese, T. Scudder, J. White, K. Vongpaseuth, and R. Ward. 2002. Thirteen Years of Monitoring the Hemlock Woolly Adelgid In New jersey Forests. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), *Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ*. N.J. Agricultural Experiment Station Rutgers. 50-60 p.
- Mausel, D.L.; Salom, S.M.; Kok, L.T.; Davis, G.A. 2010. Establishment of the hemlock woolly adelgid predator, *Laricobius nigrinus* (Coleoptera: Derodontidae), in the eastern United States. *Environmental Entomology* 39: 440–448.
- McAvoy, T., W. Mays, S.M. Salom and L.T. Kok. 2002. Preliminary report of the impact of Merit (Imidacloprid) on hemlock woolly adelgid (*Adelges tsugae*) and

- non-target species. Department of Entomology, Virginia Polytech Institute and State University, Blacksburg, VA. Unpub. Report. 14 p.
- McAvoy, T.J.; Mayfield, A.E., III; Salom, S.M. 2019. Hemlock Health Assessment, HWA, and EHS Sampling, Revised September 2019. Department of Entomology, Virginia Tech, Blacksburg, Virginia. Accessed 8 Oct 2019 at <http://hiro.ento.vt.edu/pdb/>.
- McClure, M.S. 1989. Evidence of a polymorphic life cycle in the hemlock woolly adelgid, *Adelges tsugae* (Homoptera: Adelgidae). *Ann. Entom. Soc. Am.* 82:50-54.
- McClure, M.S. 1992a. Effects of implanted and injected pesticide and fertilizers on the survival of *Adelges tsugae* (Homoptera: Adelgidae) and on the growth of *Tsuga canadensis*. *Journal Econ. Entomol.* 85(2) 468-472.
- McClure, M.S. 1992b. Hemlock woolly adelgid. *American Nurseryman* 175(6): 82-89.
- McClure, M.S. 1995. Managing hemlock woolly adelgid in ornamental landscapes. Bulletin 925. Connecticut Agricultural Experiment Station. 7 p.
- McClure, M.S. 1996. Biology of *Adelges tsugae* and its potential for spread in the Northeastern United States. In: Salom, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), *Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 16-25.*
- McClure, M.S. 2001. Biological control of hemlock woolly adelgid in the Eastern United States. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-2000-08. 10 p.
- McClure, M.S. 2002a. The Elongate Hemlock Scale, *Fiorinia externa* Ferris (Homoptera: Diaspididae): A New Look at an Old Nemesis. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), *Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers.* 248-253 p.
- McClure, M.S. 2002b. Pest Alert: Elongate Hemlock Scale. USDA, Forest Service, Northeastern Area, Morgantown, WV, NA-PR-01-02. 2p.
- McClure, M.S. and C.A.S-J. Cheah. 1998. Released Japanese ladybugs are multiplying and killing hemlock woolly adelgids. *Frontiers of Plant Science.* 50(2): 6-8 p.
- McClure, M.S. and C.A.S-J. Cheah. 2002. Establishing *Pseudoscymnus tsugae* Sasaji and McClure (Coleoptera:Coccinellidae) for the biological control of the hemlock woolly adelgid, *Adelges tsugae*, Annand (Homoptera:Adelgidae), in the Eastern United States. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), *Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-*

- 7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 351-352 p.
- McClure, M.S., S.M. Salom, and K.S. Shields. 2001. Hemlock woolly adelgid. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-2001-03. 14 p.
- Miniat, C.F.; Zeitlow, D.R.; Brantley, S.T.; Brown, C.L.; Mayfield, A.E., III; Jetton, R.M.; Rhea, J.R.; Arnold, P. 2020. Physiological responses of eastern hemlock (*Tsuga canadensis*) to light, adelgid infestation, and biological control: Implications for hemlock restoration. *Forest Ecology and Management* (in press).
- Montgomery, M.E. 1999. Woolly adelgids in the southern Appalachians: Why they are harmful and prospects for control. In: Gibson, P. and C. Parker, (Eds.), *Proceedings of the Appalachian biological control initiative workshop*. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-98-14. 59 p.
- Montgomery, M.E. and S.M. Lyons. 1996. Natural enemies of adelgids in North America: Their prospect for biological control of *Adelges tsugae* (Homoptera: Adelgidae). In: Salom, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), *Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA*. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 89-102.
- Montgomery, M.E.; Shiyake, S.; Havill, N.P.; Leschen, R.A.B. 2011. A new species of *Laricobius* (Coleoptera: Derodontidae) from Japan with phylogeny and a key for native and introduced congeners in North America. *Annals of the Entomological Society of America* 104: 389–401.
- Motley, K.; Havill, N.P.; Arsenault-Benoit, A.L.; Mayfield, A.E., III; Ott, D.S.; Ross, D.; Whitmore, M.C.; Wallin, K.F. 2017. Feeding by *Leucopis argenticollis* and *Leucopis piniperda* (Diptera: Chamaemyiidae) from the western USA on *Adelges tsugae* (Hemiptera: Adelgidae) in the eastern USA. *Bulletin of Entomological Research* 107: 699–704.
- Mullins, J.W. 1993. Imidacloprid: a new nitroguanidien insecticide. In: Duke, S.O., J.J. Menn, and J.R. Plimmer (eds.), *Pest control with enhanced environmental safety*. American Chemical Society Symposium, ASC, Washington DC: 183-189.
- Myers, W.L. and R.R. Irish. 1981. Vegetation survey of Delaware Water Gap National Recreation Area. Final Report, USDAI National Park Service.
- Onken, B., D. Souto, and R. Rhea. 1999. Environmental Assessment for the release and establishment of *Pseudosymnus tsugae* (Coleoptera: Coccinellidae) as a biological

- control agent for the hemlock woolly adelgid. USDA, Forest Service, Morgantown, WV.
- Onken, B. and D. Souto. 2006. Hemlock Woolly Adelgid Newsletter, Issue No. 7. USDA, Forest Service, Forest Health Protection.
- Perez, J. H. 2000. Bird Point Count Survey Along the Bluestone River. Unpublished field notes, Resources Management, National Park Service, Glen Jean, WV.
- Perez, J.H. 2005. Hemlock Woolly Adelgid Suppression Program – Proposed Action for Fiscal Year 2006. USDI National Park Service.
- Perez, J. 2007. Hemlock Woolly Adelgid Control Project New River Gorge National River, Gauley River National Recreation Area, Bluestone National Scenic River, 2006 Annual Report. USDI, National Park Service. 10p.
- Quimby, J. 1996. Value and importance of hemlock ecosystems in the eastern United States. In: Salm, T.C. Tigner, and R.C. Reardon, eds. Proceedings of the First Hemlock Woolly Adelgid Review, Charlottesville, VA, 1995. USDA Forest Service, Forest Health Technology Enterprise Team-Morgantown, WV. FHTET 96-10. pp1-8.
- Rhea, J.R. 1996. Preliminary results for the chemical control of hemlock woolly adelgid in ornamental and natural settings. In: Salm, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 89-102.
- Sasaji, H. and M.S. McClure. 1997. Description and distribution of *Pseudoscytnus tsugae* sp. Nov. (Coleoptera: Coccinellidae), an important predator of hemlock woolly adelgid in Japan. *Annals of the Ent. Soc. Am.*, 90:563-578.
- Schroeder, M.E. and R.F. Flattum. 1984. The mode of action and neurotoxic properties of the nitromethylene heterocycle insecticides. *Pestic. Biochem. Physiol.* 22: 148-160.
- Schweitzer, D. 1994. Hemlock woolly adelgid and native hemlock lepidoptera. Memorandum to state Natural Heritage Programs and stewardship staff at The Nature Conservancy offices in the ERO states, and NC, SC, GA, and Great Smokey Mountains National Park. (May 19).
- Silcox, C.A. 2002. Using imidacloprid to control hemlock woolly adelgid in the Eastern United States. In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 280-287 p.

- Smith, S.F. and V.A. Krischik. 1999. Effects of systemic imidacloprid on *Coleomegilla maculate* (Coleoptera: Coccinellidae). *Envir. Entomol.* 28(6): 1189-1195.
- Sussky, E.M.; Elkinton, J.S. 2015. Survival and near extinction of hemlock woolly adelgid (Hemiptera: Adelgidae) during summer aestivation in a hemlock plantation. *Environmental Entomology* 44: 153–159.
- Tattar, T.A., J.A. Dotson, M.S. Ruizzo, and V.B. Bruce. 1998. Translocation of imidacloprid in three tree species when trunk and soil injected. *Journal of Arboriculture* 24: 54-56.
- Tattar, T.A. and S.J. Tattar. 1999. Evidence of the downward movement of materials injected into trees. *Journal of Arboriculture* 25(6): 325-332.
- USDA Animal and Plant Health Inspection Service. 2002. Draft. Use of Imidacloprid formulations for the control and eradication of wood boring pests: Assessment of the potential for human health and environmental impacts.
- Van Driesche, R.G. S. Healy and R.C. Reardon. 1996. Biological Control of Arthropod Pests of the Northeastern and North Central Forest in the United States: A Review and Recommendations. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-19: 10.
- Steward, V.B. and T.A. Horner. 1994. Control of hemlock woolly adelgid using soil injection of systemic insecticides. *J. of Arboriculture* 20(5):287-288.
- Wallace, M.S. and F.P. Hain. 1998. The effects of predators of the hemlock woolly adelgid in north Carolina and Virginia. USDA, Forest Service. Hemlock Woolly Adelgid Newsletter # 3: 3.
- Webb, R.E., J.R. Frank, and M. J. Raupp. 2003. Eastern hemlock recovery form hemlock woolly adelgid damage following Imidacloprid therapy. *Journal of Arboriculture*. 29(5): 298-302.
- Yamasaki, M., R.M. DeGraaf, and J.W. Lanier. 2000. Wildlife habitat associations in eastern hemlock – birds, smaller mammals, and forest carnivores. In: *Proceedings of a Symposium on Sustainable Management of Hemlock Ecosystems in Eastern North America*, edited by K.A. McManus, K.S.Shields, and S.R.Souto. pp.135-141.
- Young, J.A., D.R. Smith, C.D. Snyder, and D. P. Lemarie. 1998. A landscape-based sampling design to assess biodiversity losses from eastern hemlock decline.